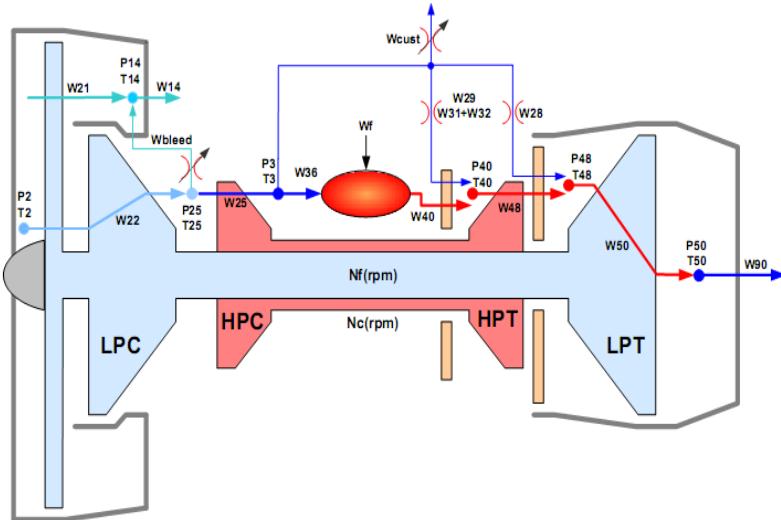
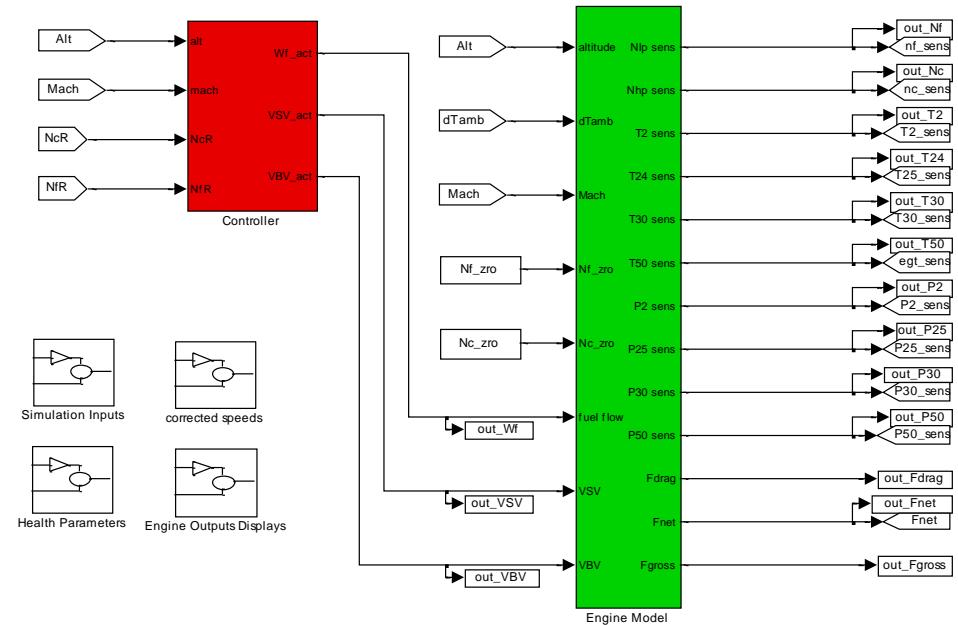


Commercial Modular Aero Propulsion System Simulator 40,000 (C-MAPSS40k)



C-MAPSS40k
PAX200 Commercial Turbofan Engine and Controller Models



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Overview

- Background
- History of NASA Propulsion System Simulations
- C-MAPSS40k
 - Open Loop Engine
 - Baseline Controller
 - Capabilities and Examples
 - Interfaces
- Current Status and Availability
- Questions



Background

- Developed under Integrated Propulsion Controls & Dynamics (IPCD) task of IRAC
- New dynamic flight test data from a highly instrumented engine in 40,000 lbf thrust class
- For IRAC it is necessary to compare alternate controller strategies to a baseline approach
- This drove the development of a new engine simulation with an “industry-standard” controller
- New simulation based on past modeling approach

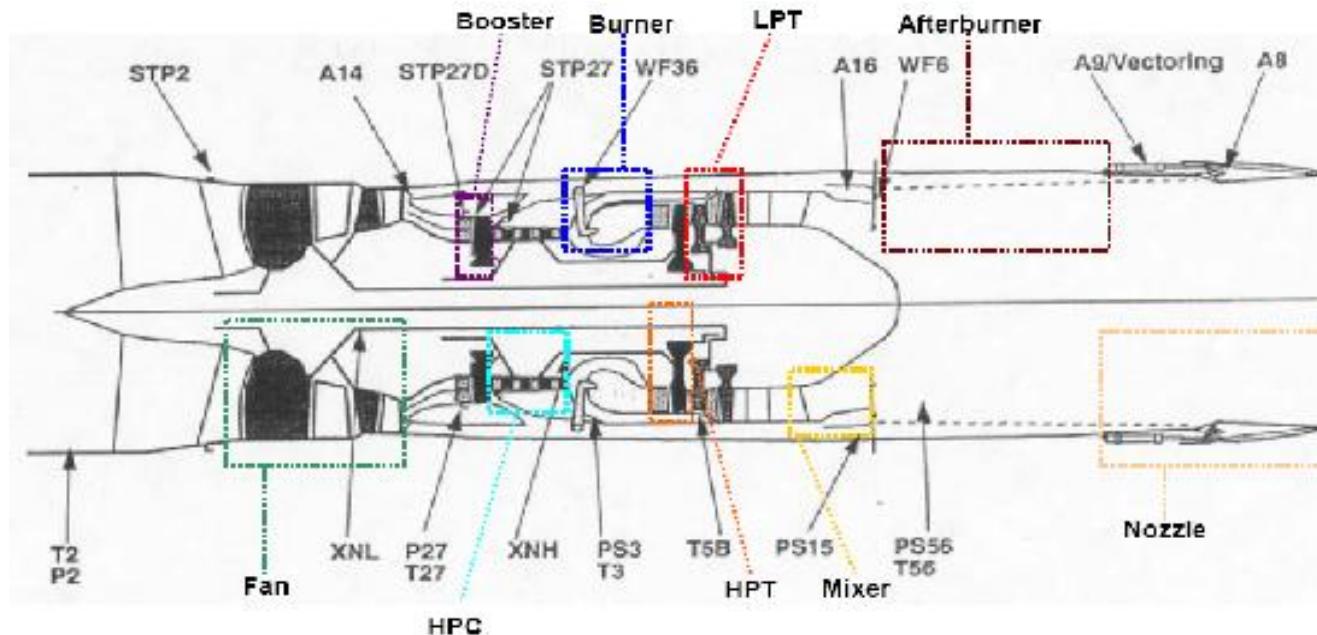


NASA Propulsion System Simulations

- MAPSS, C-MAPSS, and now C-MAPSS40k
- Goals:
 - Publicly-Available (no proprietary data)
 - Steady-state and transient test capability
 - Modular
 - Developed in MATLAB/Simulink for ease of use

Modular Aero Propulsion System Simulator (MAPSS)

- Military Low Bypass Turbofan Engine Simulation



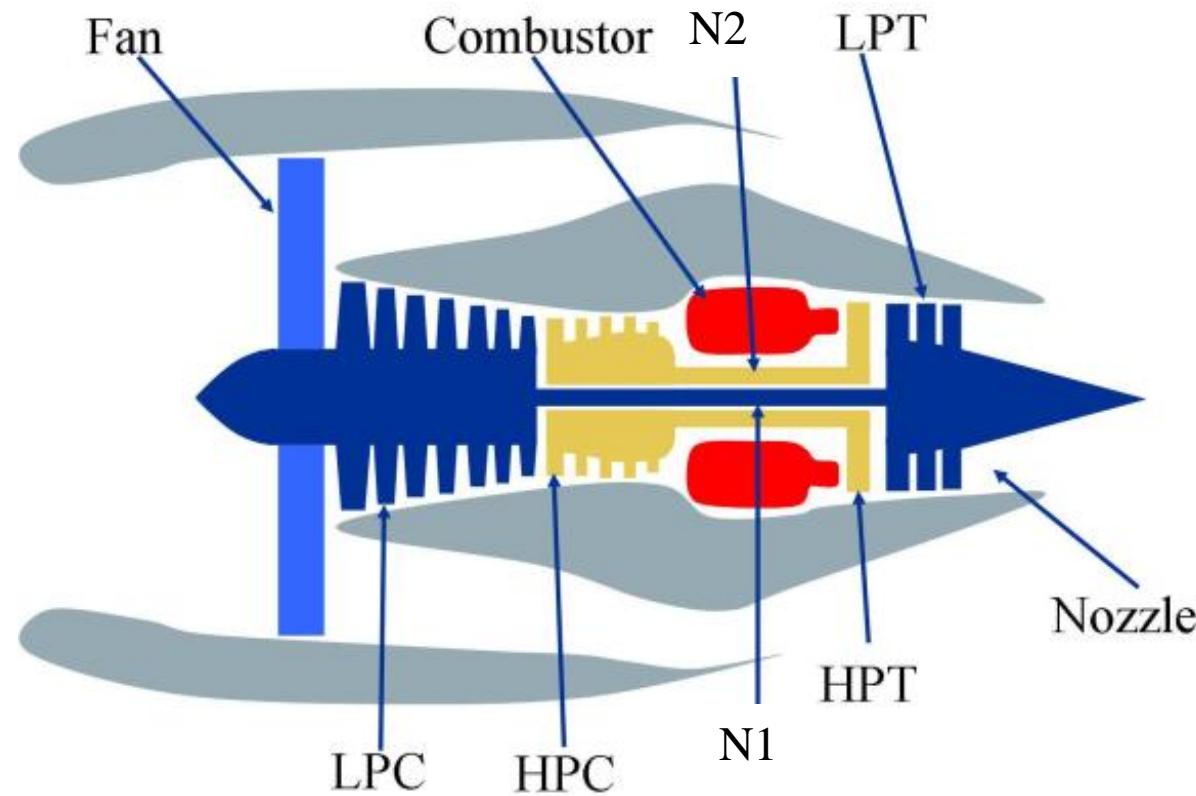


MAPSS Info

- GUI environment to develop advanced control algorithms
- Generate state-space linear models at user-specified operating points
- Transient simulation to verify and validate control algorithms
- MAPSS Availability:
<http://www.grc.nasa.gov/WWW/cdtb/software/index.html>

Commercial Modular Aero Propulsion System Simulator (C-MAPSS)

- 90,000 Lb Thrust Class High Bypass Turbofan Engine Simulation



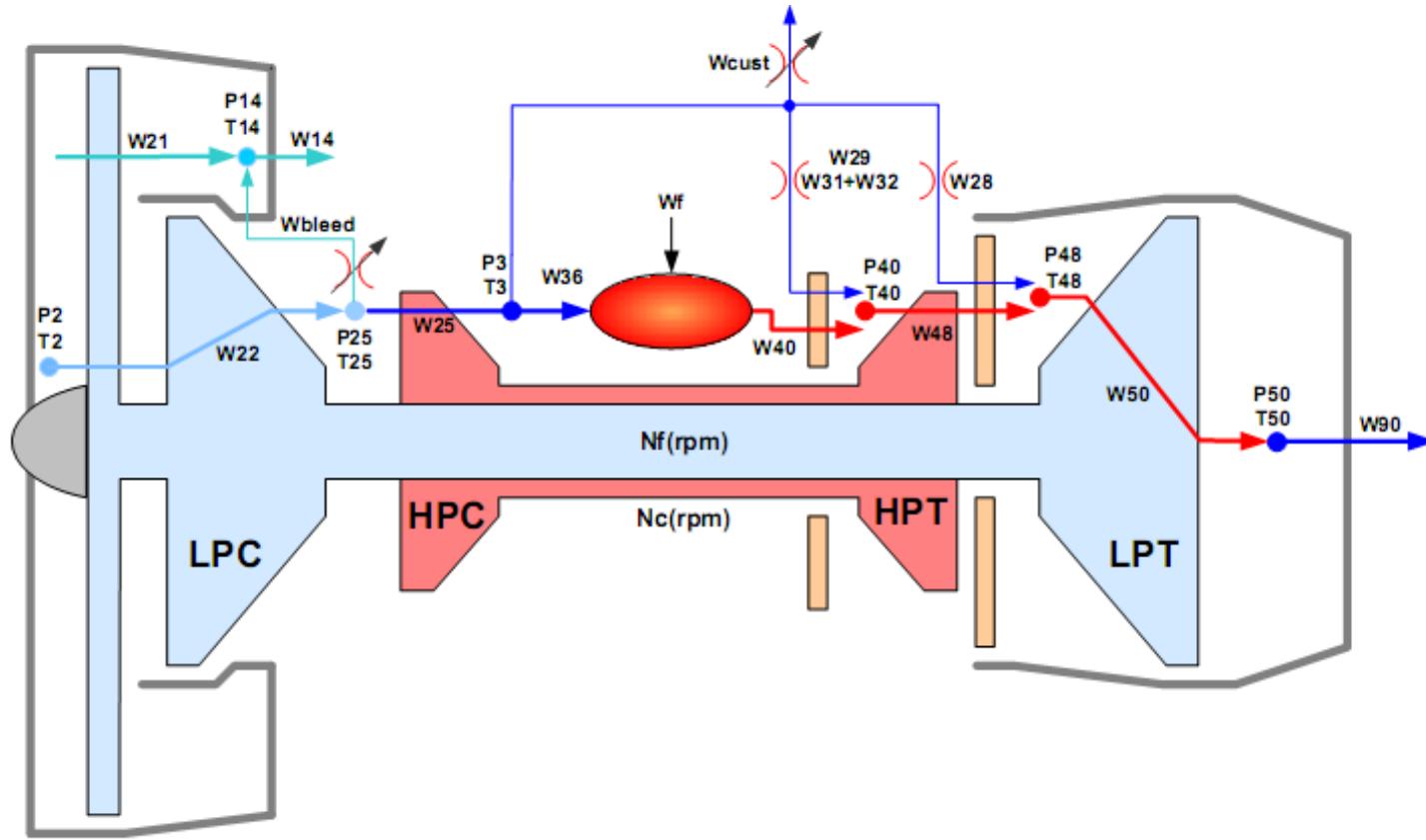


C-MAPSS Info

- GUI environment
- Contains atmospheric model allowing full envelope operation
- Generate state-space models at user-specified operating points
- Capability to compare linear model to non-linear model
- Transient simulations
- Runs Faster than real-time
- Availability:
<http://www.grc.nasa.gov/WWW/cdtb/software/index.html>

Commercial Modular Aero Propulsion System Simulator 40,000 (C-MAPSS40k)

- 40,000 Lb Thrust Class High Bypass Turbofan Engine Simulation

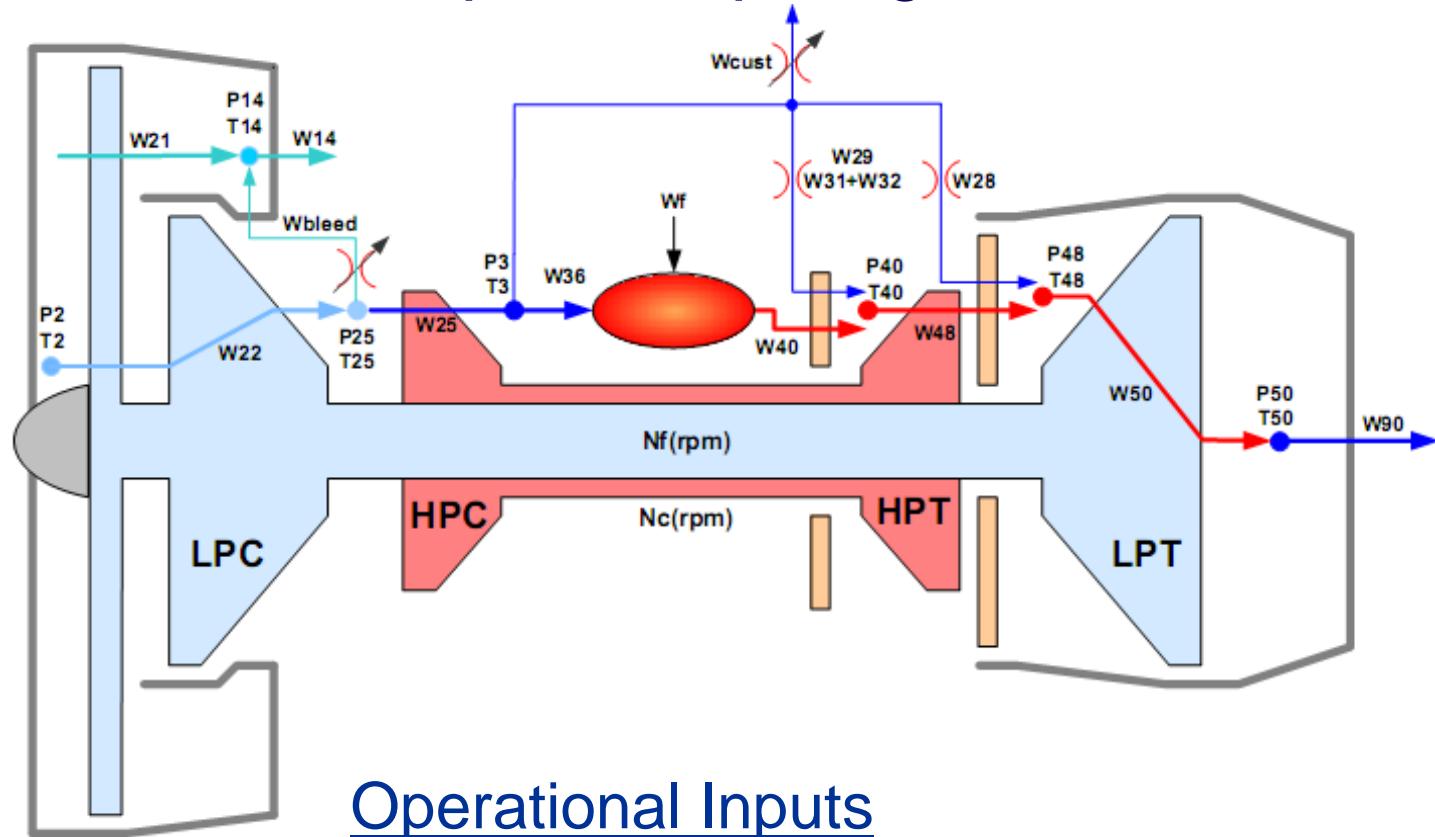




C-MAPSS40k Info

- GUI or command line driven
- Atmospheric model allowing full envelope operation
- Generate state-space models at user-specified operating points
- Capability to verify linear model against non-linear simulation
- Transient simulations
- Runs faster than real time
- Contains realistic baseline controller
- Contains detailed stall margin calculations
- Tuned to test data from a highly instrumented engine

Open Loop Engine



Control Inputs

- Wf
- VBV
- VSV

Operational Inputs

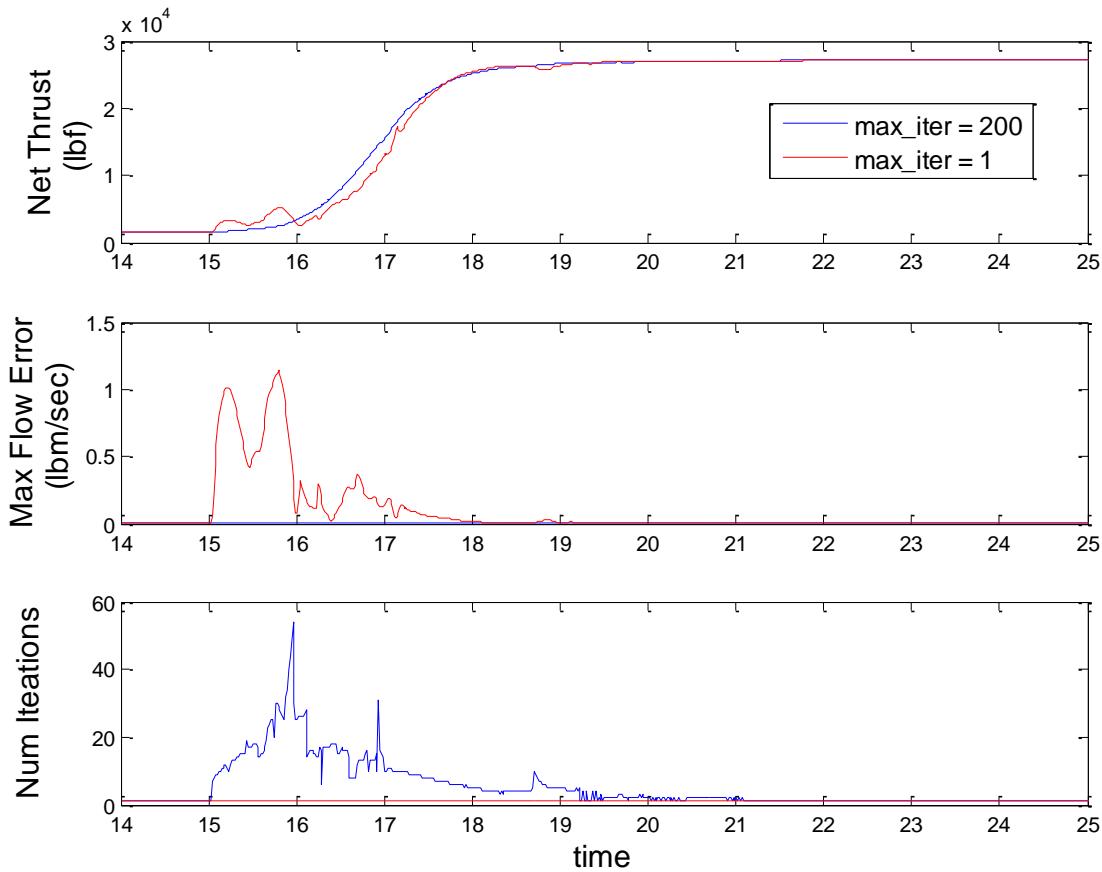
- Customer Bleed
- Power Extraction
- Deterioration Level
- Health Parameters

Outputs

- Typical Sensors
- Thrust
- Stall Margins

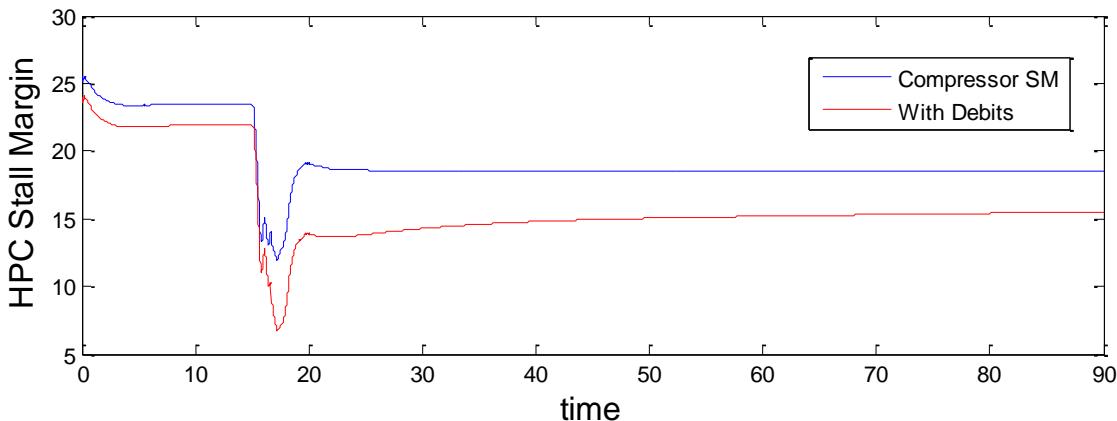
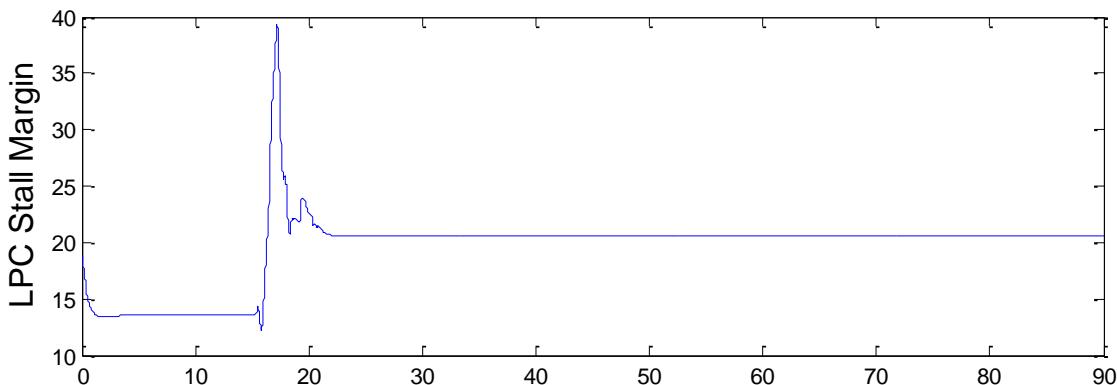
Iterative Solver

- Flow errors balanced at every time step unlike C-MAPSS
- Newton-Raphson Method
- Configurable Limits:
 - Max # Iterations
 - Allowable Flow Error
- On a “current” laptop if $\text{num_iter} < 63$ then runs in real-time



Stall Margin Calculations

- Model Compressor Stall Margin
- Model Stall Margin Debts due to:
 - Rotor Tip Clearance Changes
 - Heat Transfer between case and rotor
 - Engine Deterioration

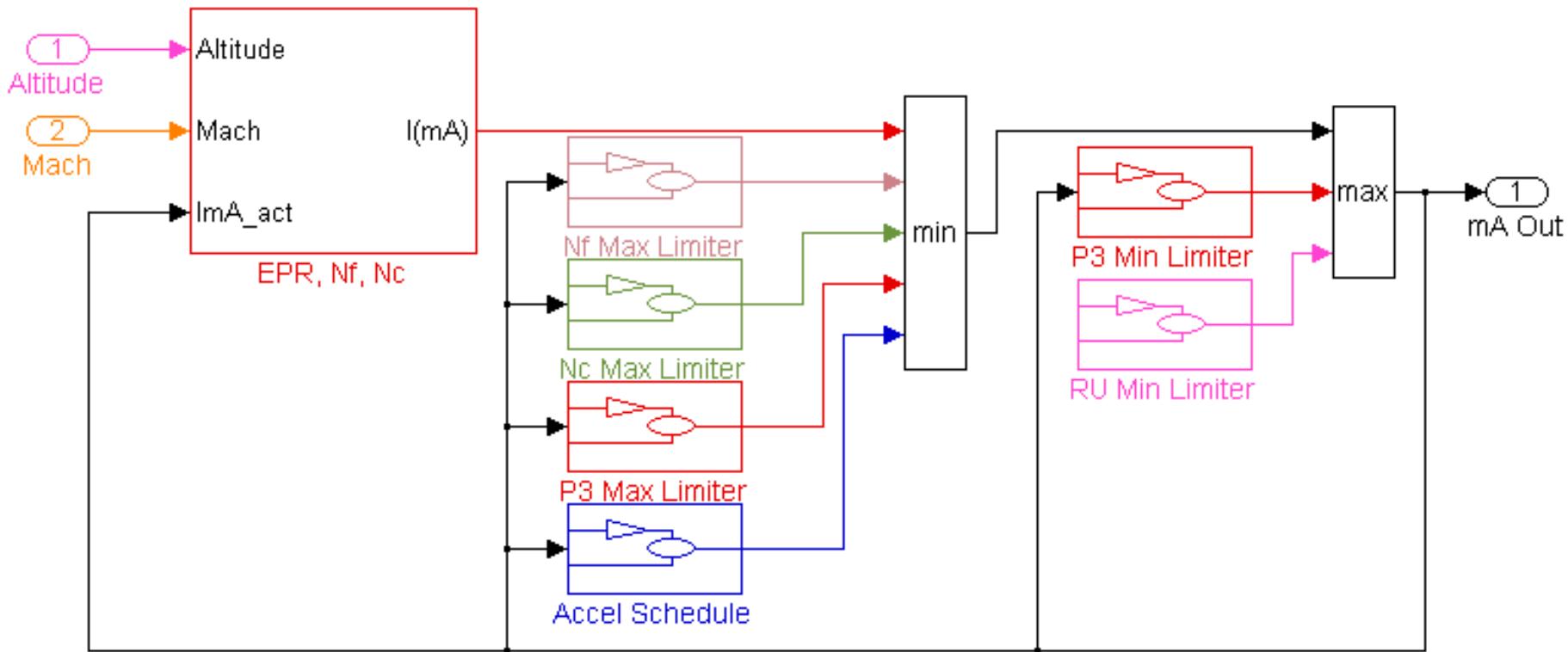




Baseline Controller

- Designed to be representative of current industry
- Choice of two control variables
 - Engine Pressure Ratio (EPR)
 - Fan Speed (Nf)
- Limits:
 - Rotor speeds
 - Min and max combustor pressure
 - Acceleration schedule
 - Min Wf/P3
- Controller tested against FAR 33.73 – Thrust or Power Response

Baseline Controller Architecture



- MIN/MAX structure
- “mA Out” is command to FMV
- All steady-state controllers and limiters are PI



Integrator Wind-Up Protection

- Necessary to prevent Integrator Wind-Up and ensure bump-less transfer when switching between limits
- Feedback “selected” Wf command to each PI-controller

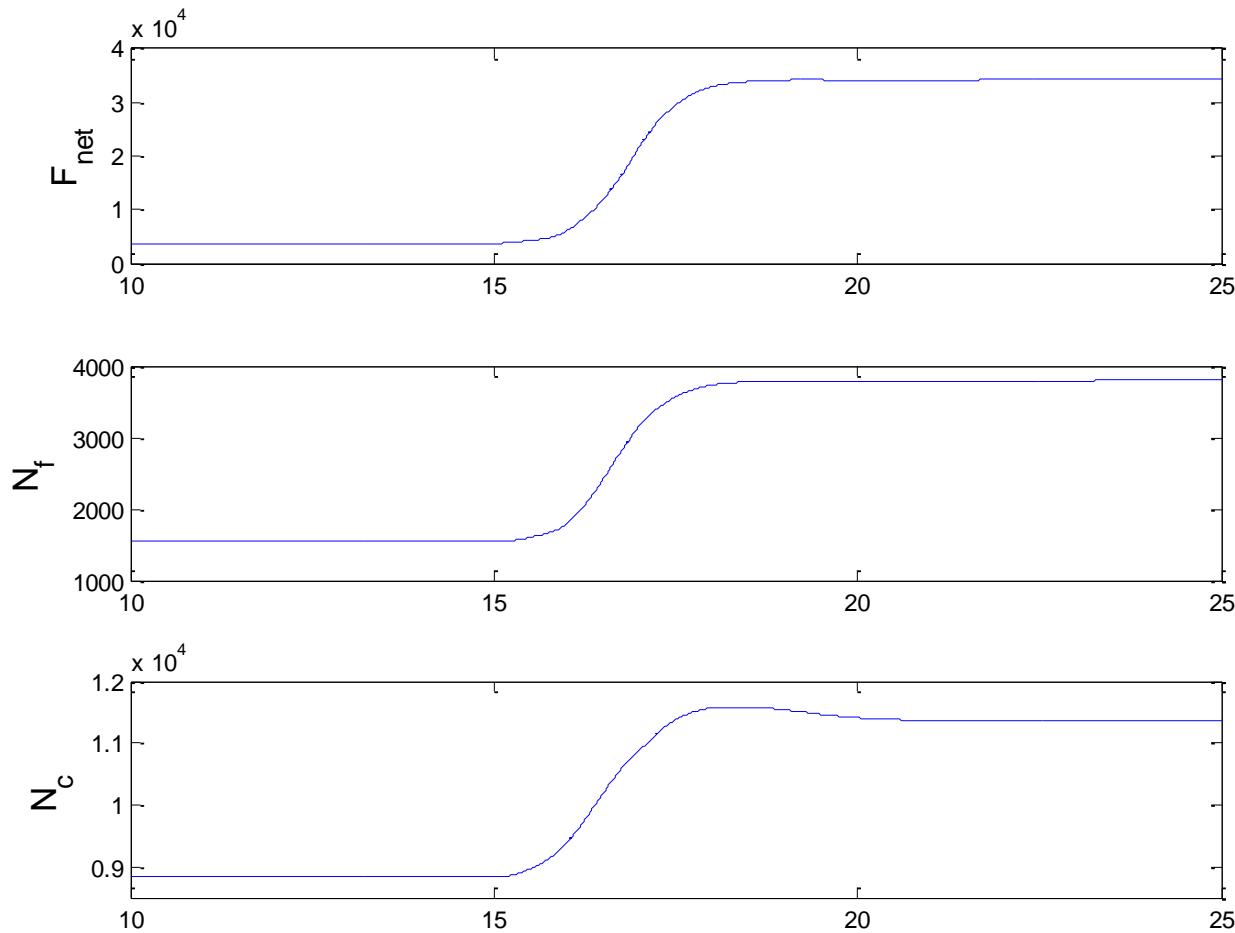
$$u = K_p * e + K_i \int(e - C * (u - u_{act}))dt$$

- When $u \approx u_{act}$, behaves as a typical PI-controller
- When $u \neq u_{act}$, u will follow u_{act} with a steady-state error governed by C



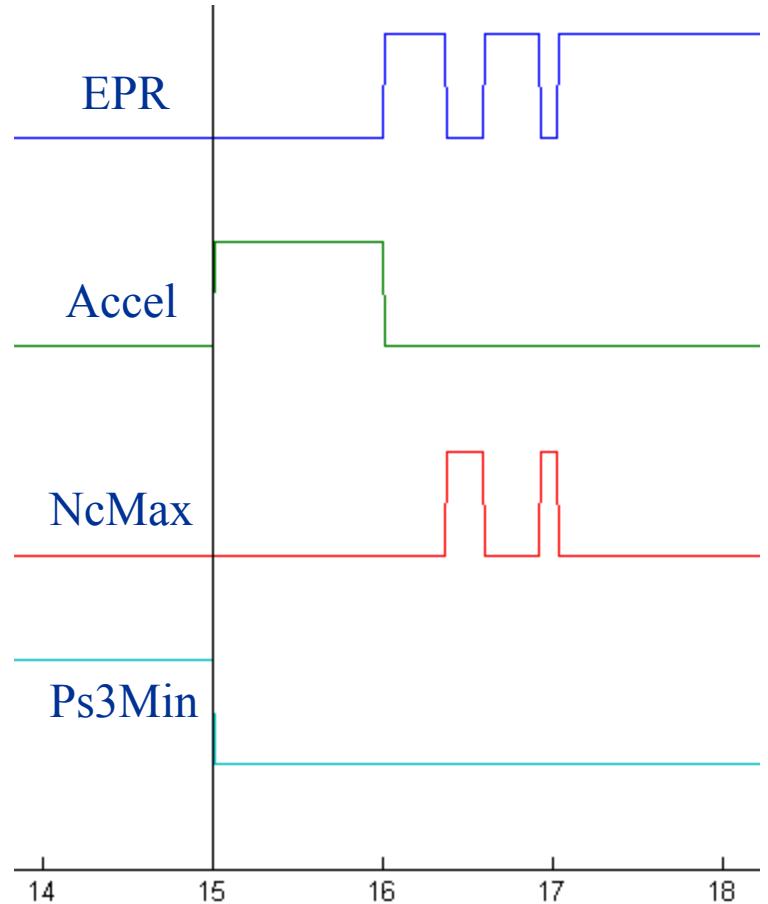
C-MAPSS40k Simulation Results

Burst from Min Idle to Full Power at Sea Level Static on Standard Day at t=15sec



Controller Operation

- Full power transient at Sea Level Static, Standard Day
- Initially at Idle
- Ultimately under EPR control
- Transient is mostly in Accel limit





Deterioration and Faults

- Two methods of simulating engine degradation
 - deterioration_level – 0 is a 50hr engine and 1 is an end-of-life engine
 - Health Parameters – modify each individual health parameter to simulate deteriorated engine
- Simulate Faults
 - Modify the health parameter time vector and any individual health parameter which corresponds to system fault.
 - Example – Foreign Object Damage

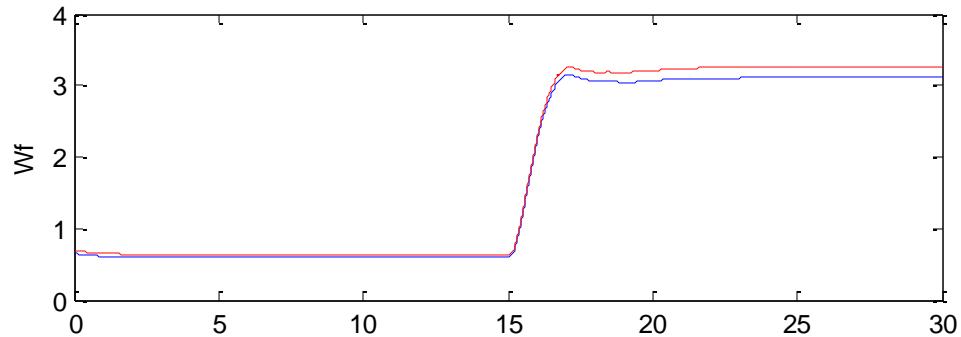
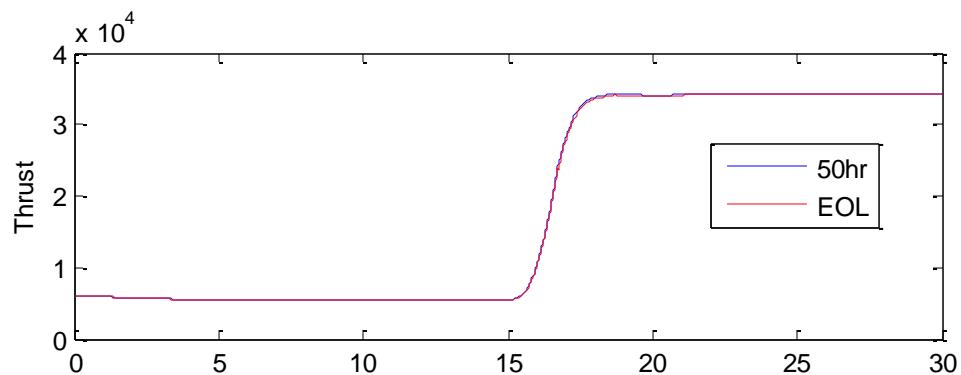


Deterioration

Compare: New Engine to End of Life Engine
@SLS, Standard Day, Min Idle to Full Power

Approx
same
thrust
response

Changed deterioration level from 0 to 1



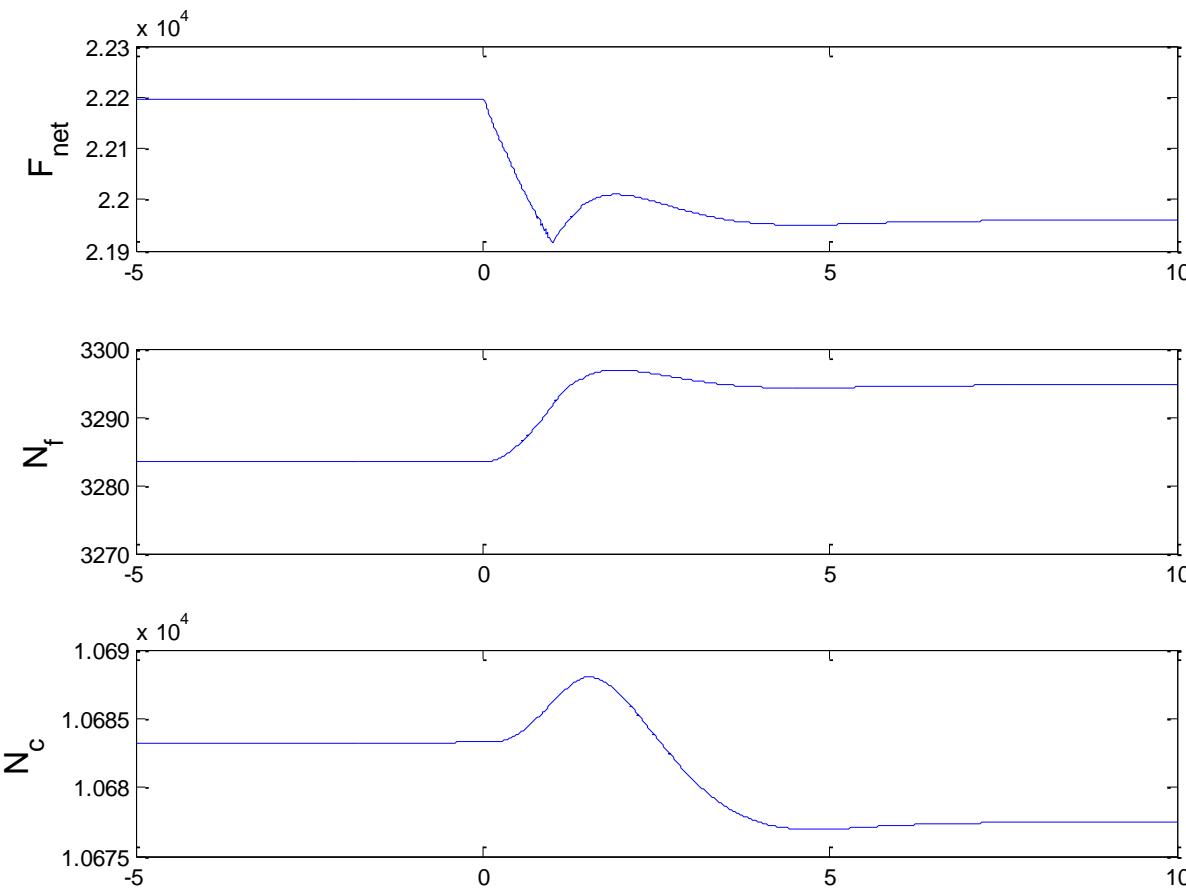
More fuel
required to
meet
demand



Simulated FOD Fault Condition

SLS, Standard Day, Mid – Power, 50 Hr Engine

4% decrease in Fan Flow, 3% decrease in Fan Efficiency





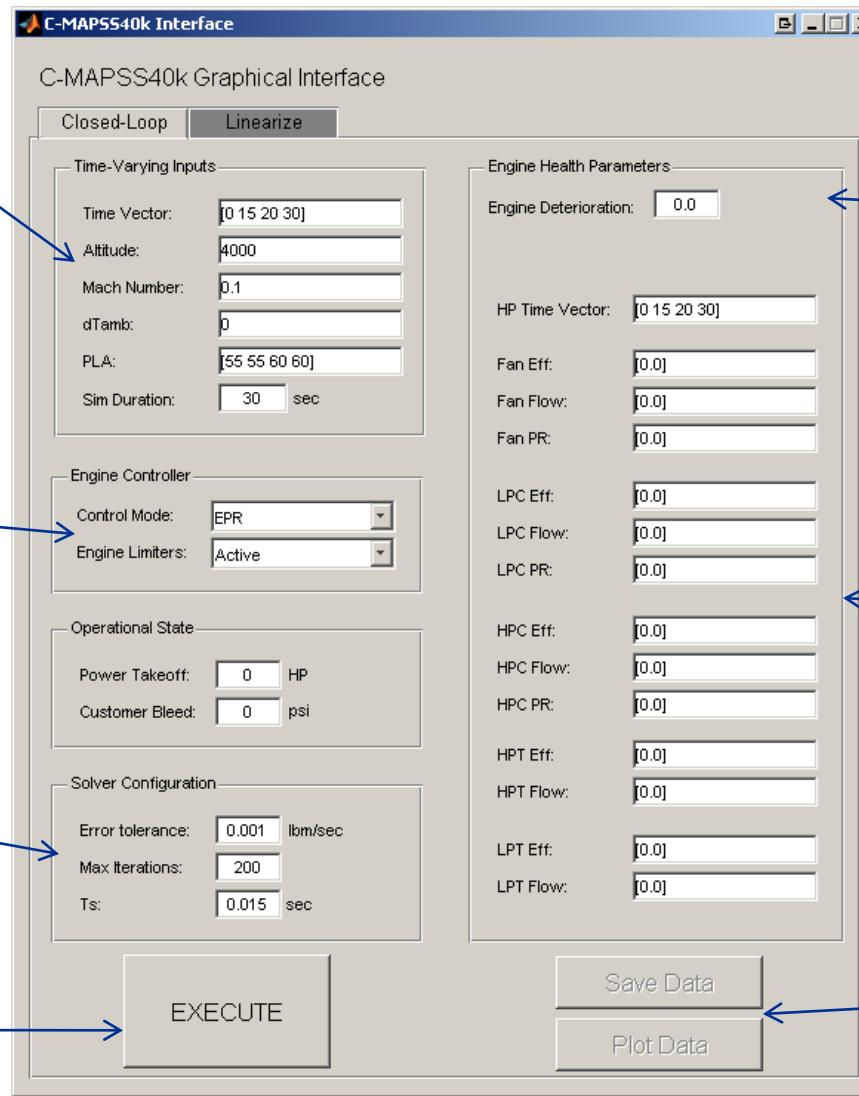
Graphical User Interface Operation

Modify flight condition

Switch Controllers

Modify Solver

Run the Simulation



Modify Engine Degradation

Modify Component Deterioration and Insert Faults

Save and Plot Data



Command Line Operation

- All options to run C-MAPSS40k contained in one file. Modify inputs in file and run setup_everything.

The screenshot shows the MATLAB 7.9.0 (R2009b) interface. The Command Window pane displays the command `>> edit('define_inputs.m')` followed by `>> setup_everything`. The Workspace pane shows a table with columns for Name and Value. The Editor pane displays the contents of the `define_inputs.m` script, which defines environmental inputs for a C-MAPSS40k simulation. The script includes sections for environmental inputs and a try-catch block for handling input validation.

```
% C-MAPSS40K -- define_inputs.m
% ****
% written by Jeff Csank and Ryan May
% NASA Glenn Research Center, Cleveland, OH
% June 4th, 2009
%
% This file contains the user defined inputs for C-MAPSS40K simulation
% ****
%
% =====
% Environmental Inputs
% =====
try
    var_names = {'t_vec','alt','MN','dTamb','PLA'};
    for i=1:length(var_names)
        eval(['var_names(i)' ' = in_' var_names(i) '']);
    end
catch
    t_vec = [0 15 20 30];
    alt = 4000; %Altitude (0 to 15,000 ft)
    MN = 0.1; %Mach Number (0 to 0.4)
    dTamb = 0; %Delta Temperature (-30 to +50)
    PLA = 55; %PLA or Power Code (40 to 80.5)
end
%
```



Linearization

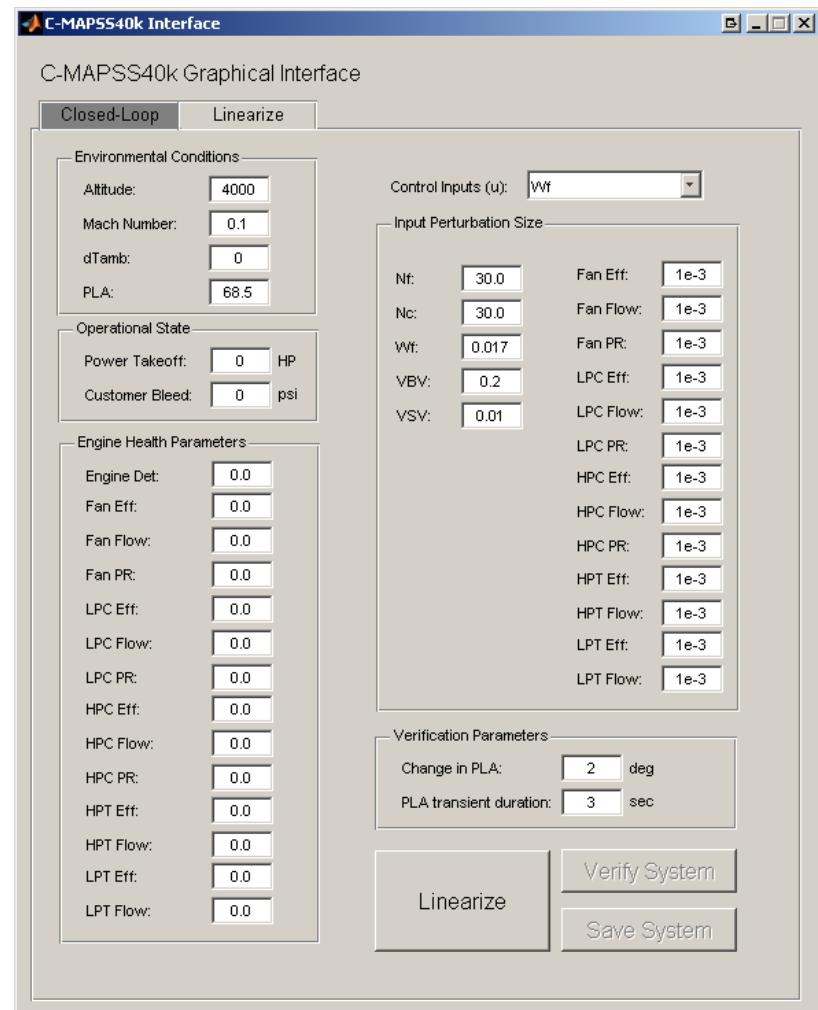
- Linearize 2 systems with different inputs
 - Wf
 - Wf, VSV, and VBV
- Outputs
 - System in the form of:
$$\dot{x} = Ax + Bu + Lh$$
$$y = Cx + Du + Mh$$
 - Where
 - x = state variables, u = inputs, h = health parameter vector
- Verification Outputs
 - Small PLA change at the linearized flight condition
 - Compares:
 - Thrust, Fan Speed, Core Speed, T30, and T50

Linearization

- SLS, Standard Day, Mid – Power, New Engine

Enter Flight Conditions
into:
`linearize_CMAPSS40k.m`

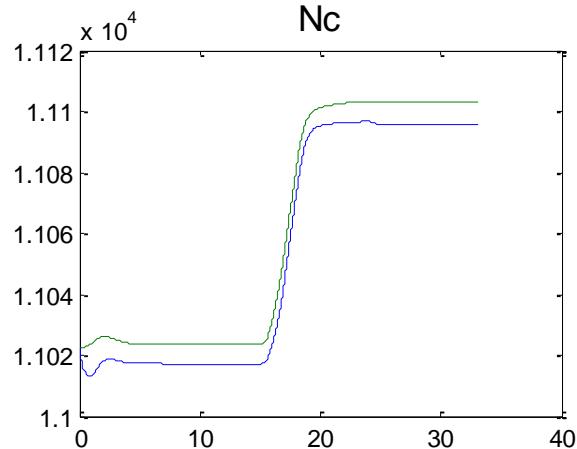
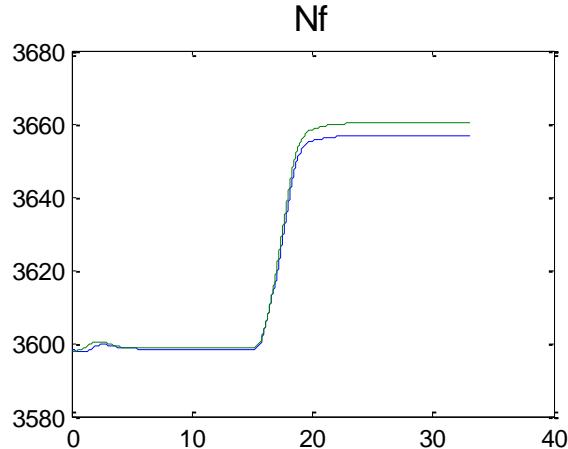
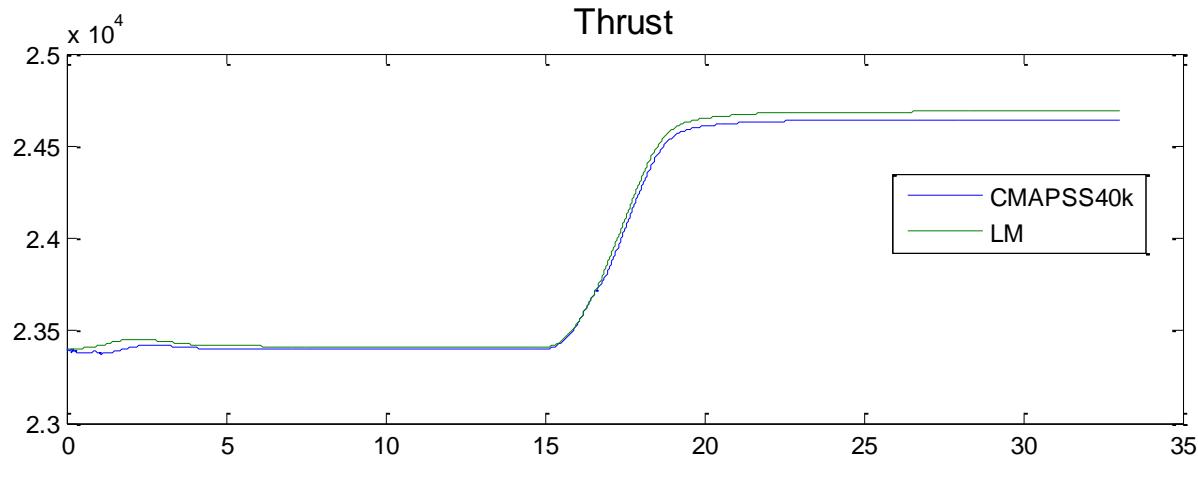
@ Command Prompt:
`>> linearize_CMAPSS40k`





Linearization Output

Mid-Power, Sea Level Static, Standard Day using default Linearization Commands





C-MAPSS40k Availability

- C-MAPSS40k is nearly complete
- C-MAPSS40k and published user's guide is planned to be available early 2010
- Check our website at:
 - <http://www.grc.nasa.gov/WWW/cdtb/software/index.html>



Summary

- C-MAPSS40k is physics based model tuned to match test data from a highly instrumented turbofan engine
- Contains an easy-to-use graphical user interface
- C-MAPSS40k is capable of running faster than real time
- Official release is scheduled for early 2010
- C-MAPSS and MAPSS are currently available for download and C-MAPSS40k will be available for download from:
<http://www.grc.nasa.gov/WWW/cdtb/software/index.html>



Thank You

Questions??